What the Standard Model may not want us to know

On the search for a nonperturbative regulator for chiral gauge theories

Dorota Grabowska, D.B.K., arXiv:1511.03649, to appear in PRL

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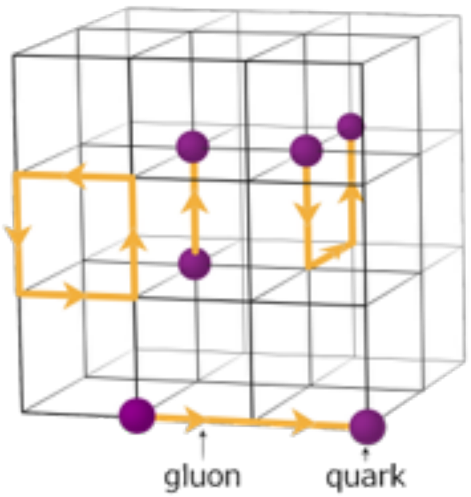
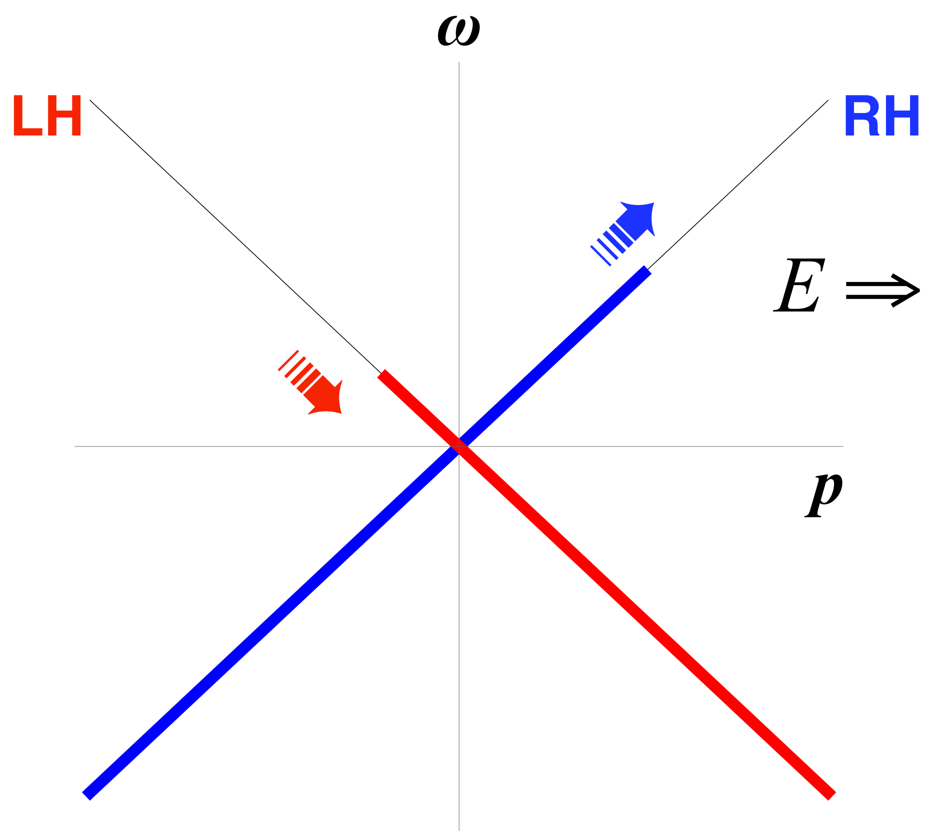
Argument for string theory?
Or might something be missing from the Standard Model?

What are the issues for chiral symmetries on the lattice?



The key is the anomaly.



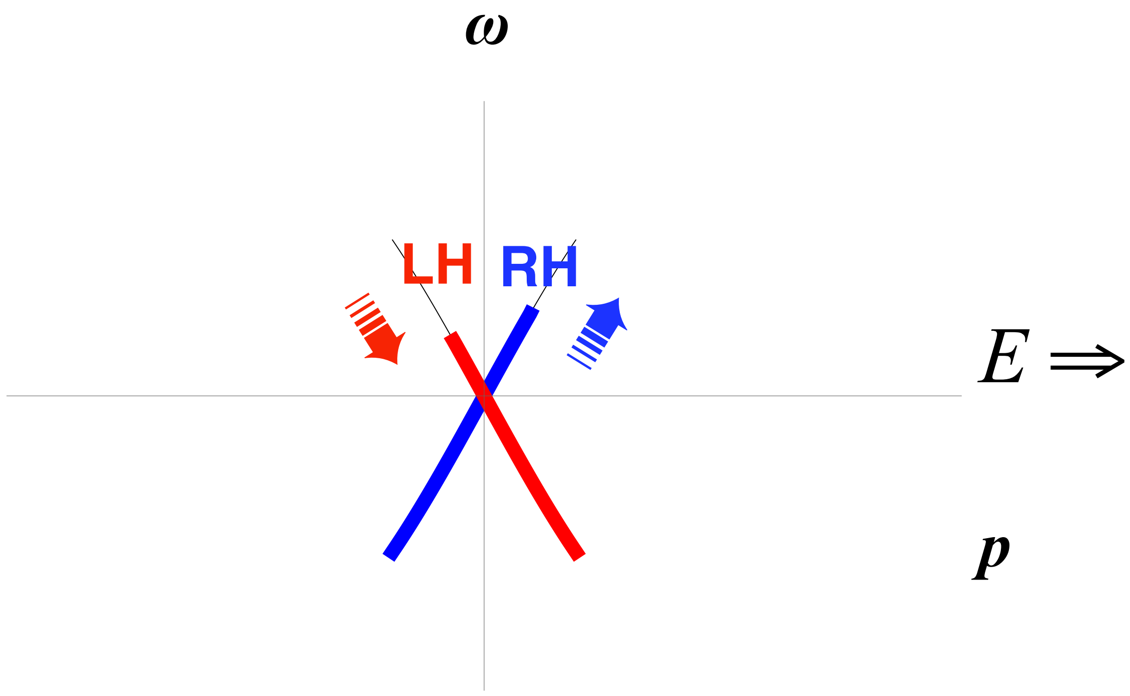
$$\mathrm{d}=(1+1): \quad \partial_\mu j_5^\mu = \frac{qE}{\pi}$$

quantum violation of a classical symmetry

In the continuum, the Dirac sea is filled…but is a Hilbert Hotel which always has room for more

Not so on the lattice:

Can reproduce continuum physics for long wavelength modes…



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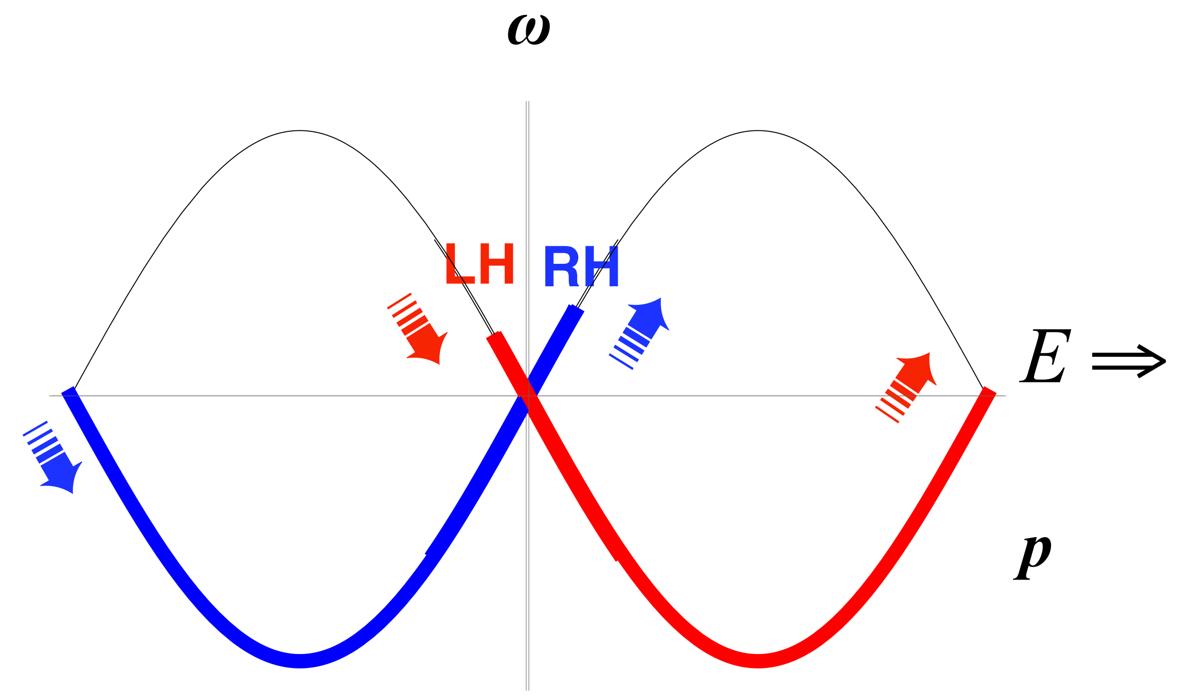

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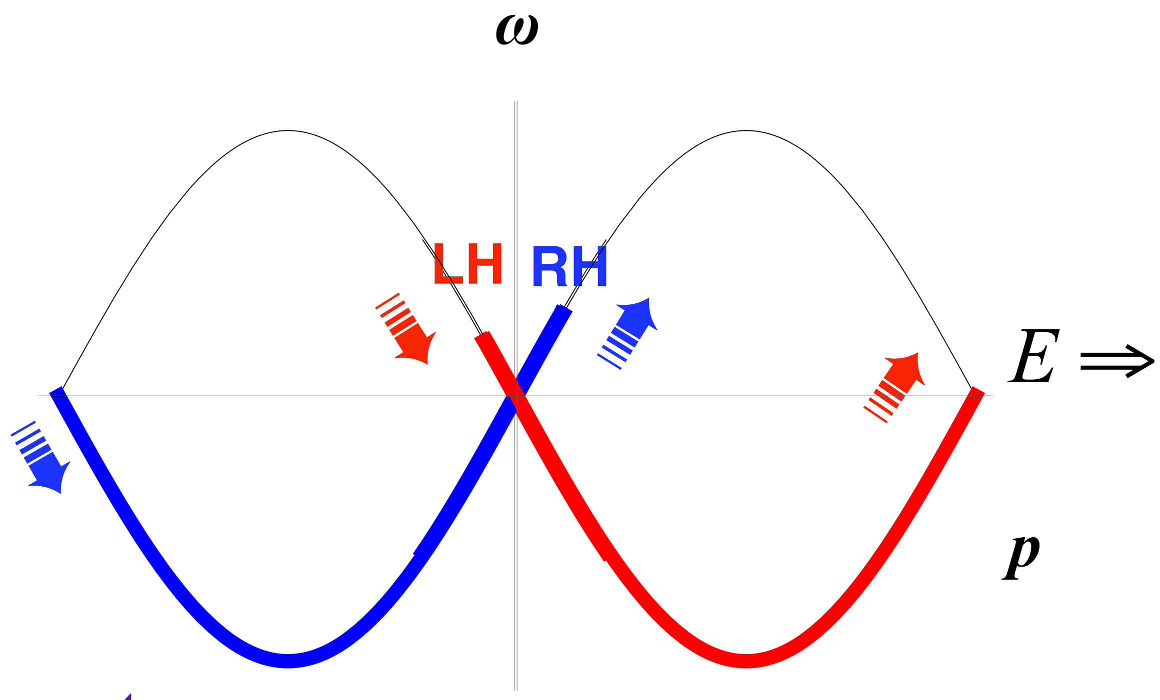

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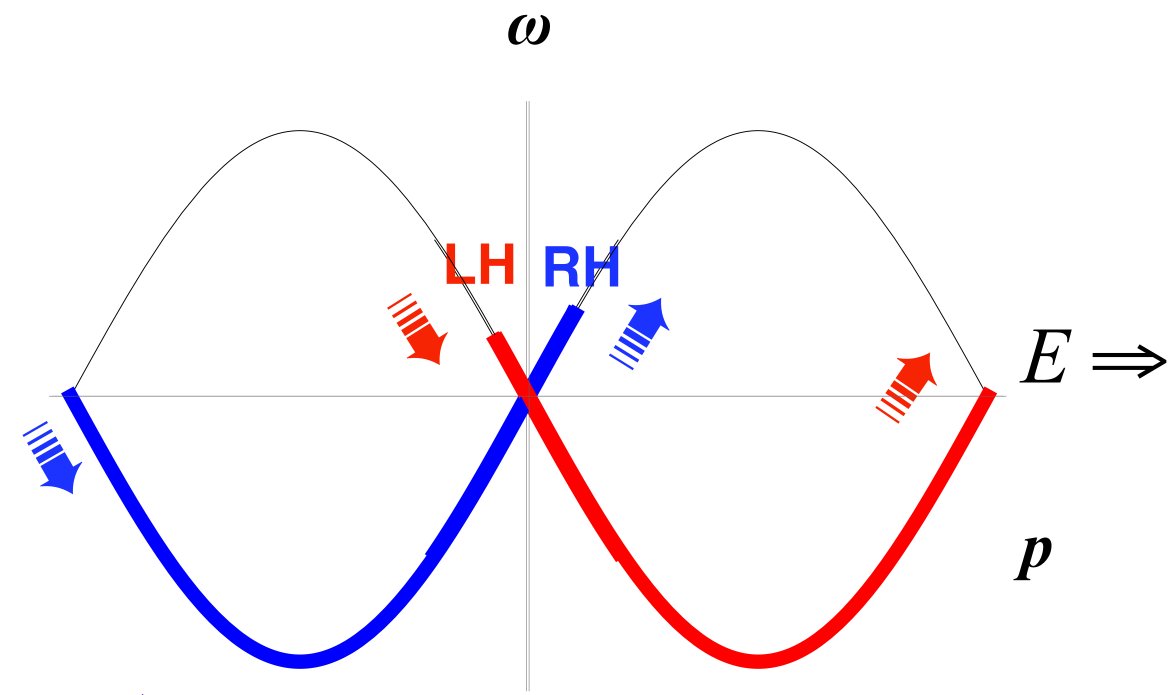

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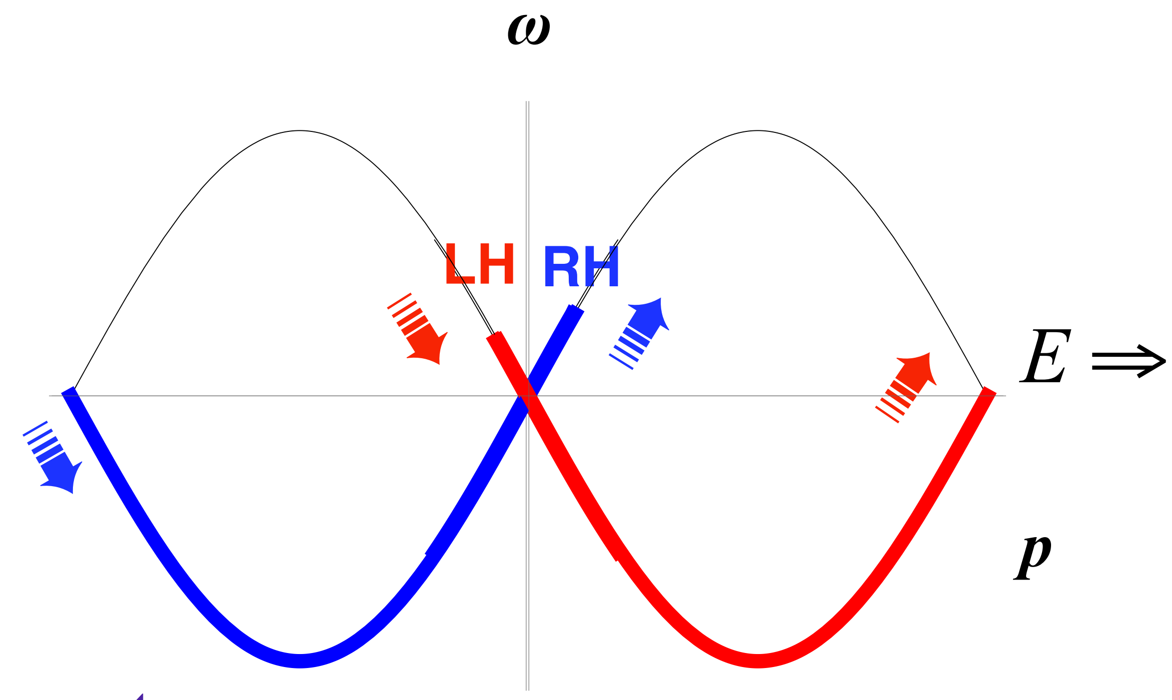

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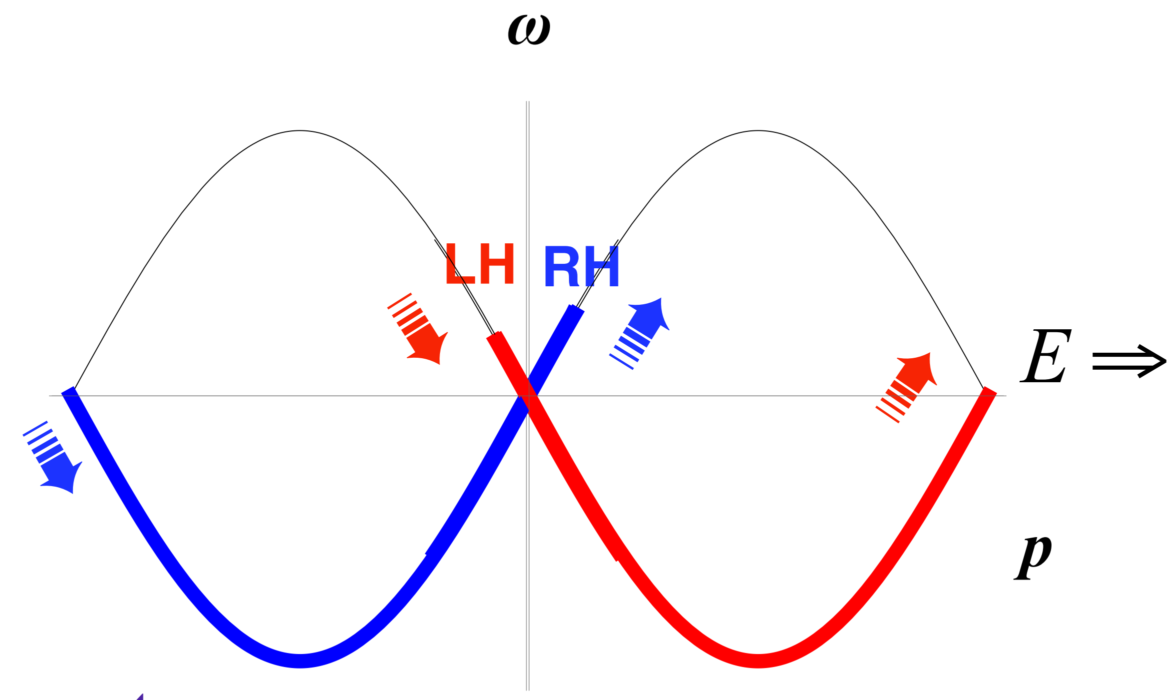

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- …these unwanted "mirror fermions" are not seen in the SM.
- The mirror fermions can be given a large mass and decoupled in a vector gauge theory, but this breaks gauge symmetry in a chiral gauge theory

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How lattice QCD with Wilson fermions reproduces the $U(1)_A$ anomaly:

Lattice covariant derivatives

$$\mathcal{L} = \bar{\psi}\left(\not{D} + m + aD^2\right)\psi$$

violates chiral symmetry

- Wilson fermions eliminate doublers by giving them a big mass
- This explicitly breaks the (global) chiral flavor symmetries of QCD
- Correct anomalous Ward identities are recovered in the continuum through fine tuning

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For chiral gauge theories, a devil's choice:

- keep the mirror fermions (not a chiral theory!)
- eliminate the mirror fermions (breaks the gauge symmetry!)

In lattice QCD (or any vector like theory): give the mirror matter fields a large mass and decouple them

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For a chiral gauge theory, break the gauge symmetry to eliminate the mirror matter?

(…and try to restore it in the continuum limit?)

Bock, Golterman, Shamir 1998, 2004

Breaking gauge symmetry opens a pandora's box of potential trouble

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Numerous attempts in the literature, but:
Every case analyzed: the mirrors do not decouple, or the whole theory becomes noninteracting…
(Golterman-Petcher-Rivas-Smit; Chen-Giedt-Poppitz)

This talk:

the mirror fermions do not become heavy, but decouple in a gauge invariant way…

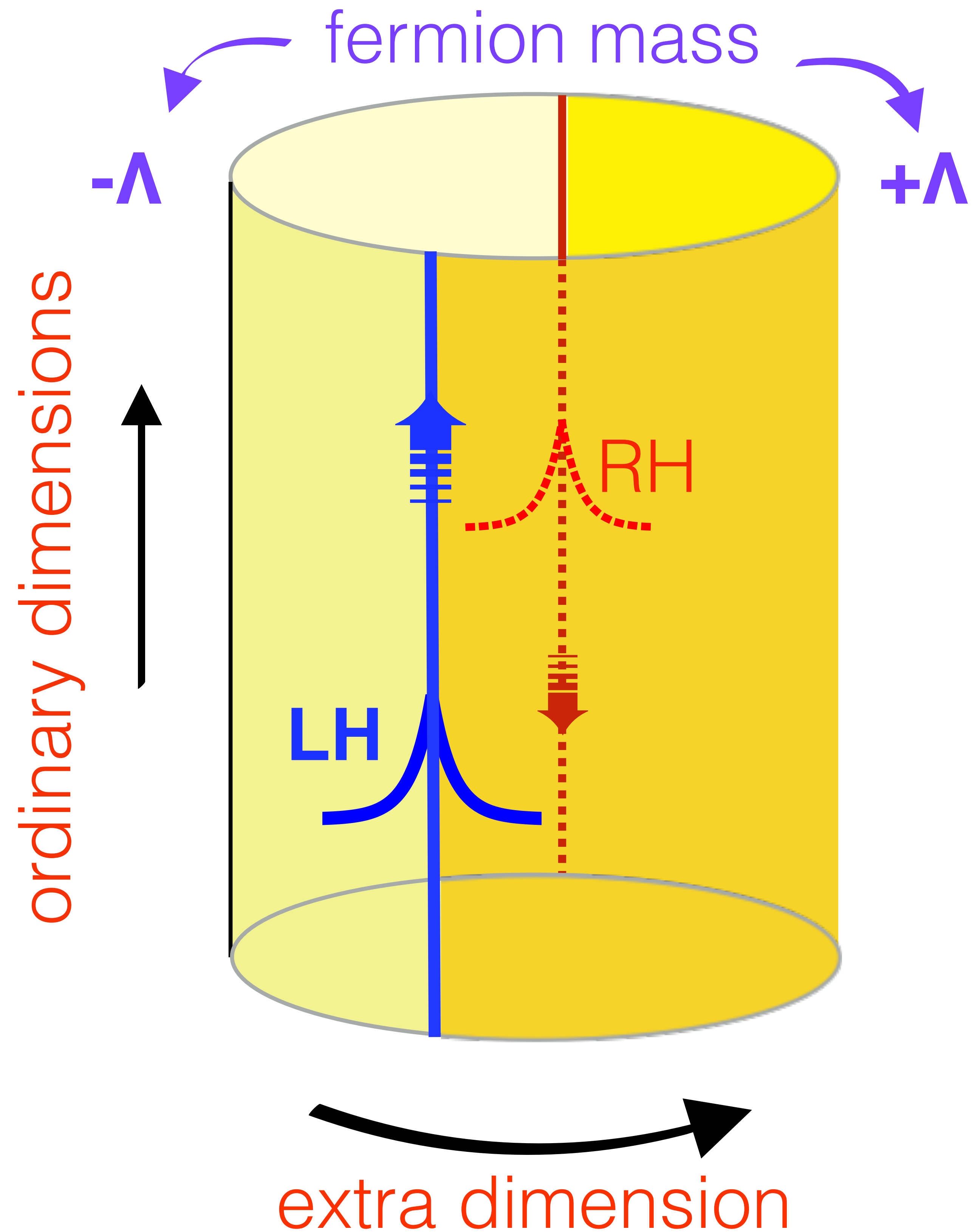
…but not entirely: still have potentially interesting nonlocal interactions through gauge topology

Starting point: domain wall fermions (aka: topological insulators)

Start with an easier problem:

realizing global chiral symmetries in QCD (DBK, 1992)

- Dirac field in compact 5th dimension
- Gauge fields constant in x_5
- Fermion mass flips sign as you go around x_5
- Find localized massless LH, RH chiral modes stuck to mass defects
- At low energy and $L_5 \Rightarrow \infty$, gauge fields see a massless Dirac fermion
- $U(1)_A$ anomaly: massive bulk fermions do not quite decouple, communicate chiral charge flow between domain walls



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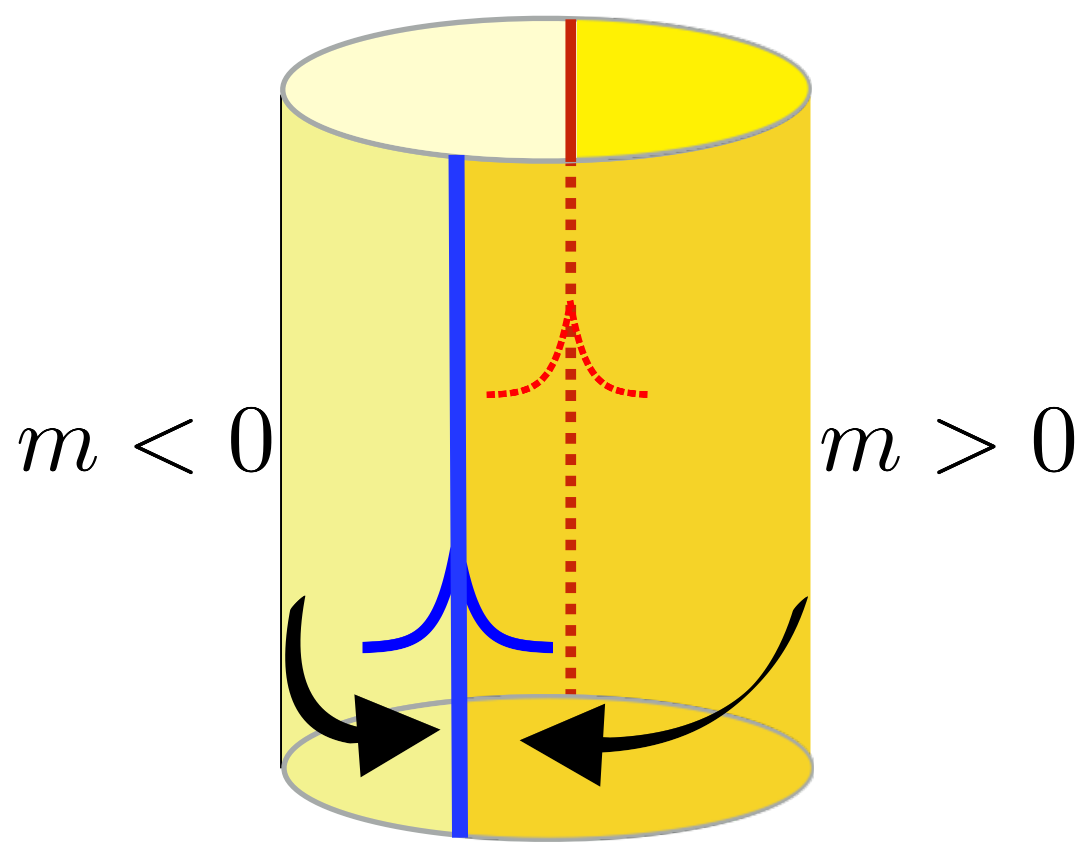
Integrating out massive fermion modes from the bulk leads to a non-decoupling term: the Chern-Simons action

Sensitive to sign of m, no decoupling as m→∞

$$S_{\text{eff}} \propto \frac{m}{|m|}\epsilon_{abcde}\mathrm{Tr}\;(A_a\partial_b A_c\partial_d A_e + \ldots)$$

Yields current that diverges where the massless fermions live:

$$\partial_\mu j_5^\mu \propto \frac{m}{|m|}\epsilon_{5bcde}\mathrm{Tr}F_{bc}F_{de}$$

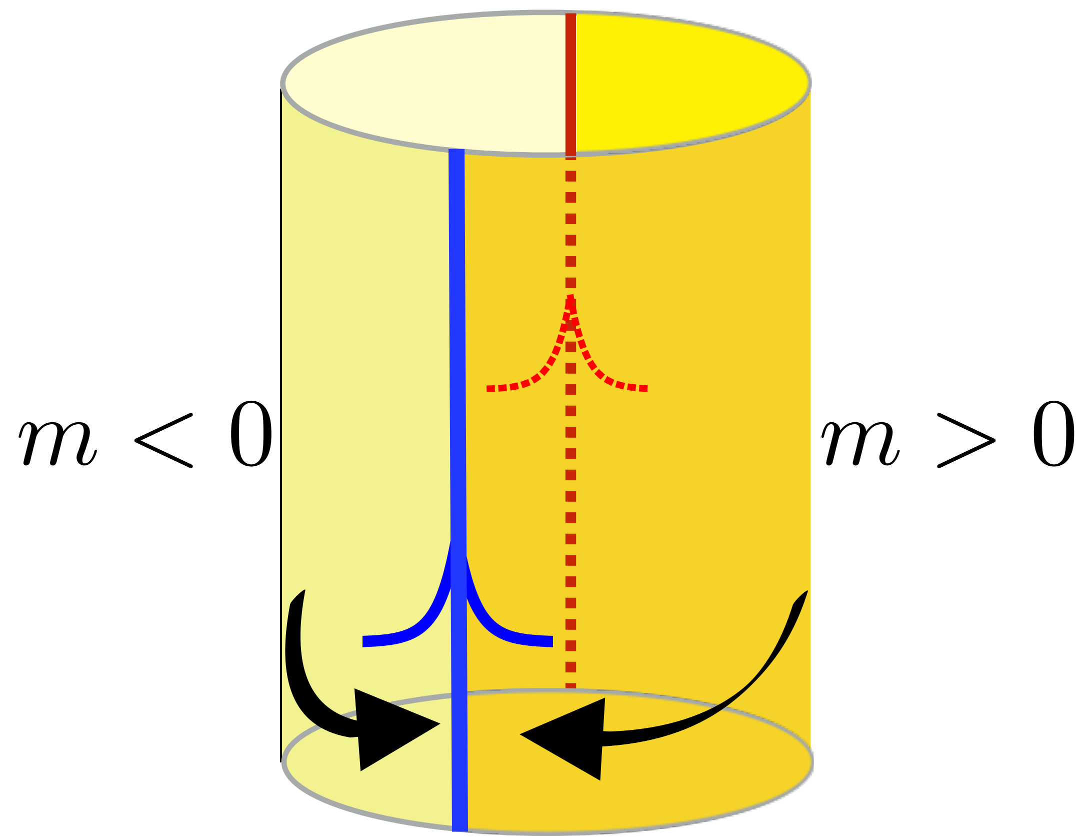


All chiral symmetry breaking due to bulk fermion mass decouples as m→∞ *except* for the anomaly…no fine-tuning needed

System is stable against radiative corrections because number of chiral zero modes is determined by **topology** (hence *topological* insulator)

The topology is not in coordinate space, but is a property of the bulk fermion dispersion relation in momentum space

(Golterman, Jansen, DBK, 1992)



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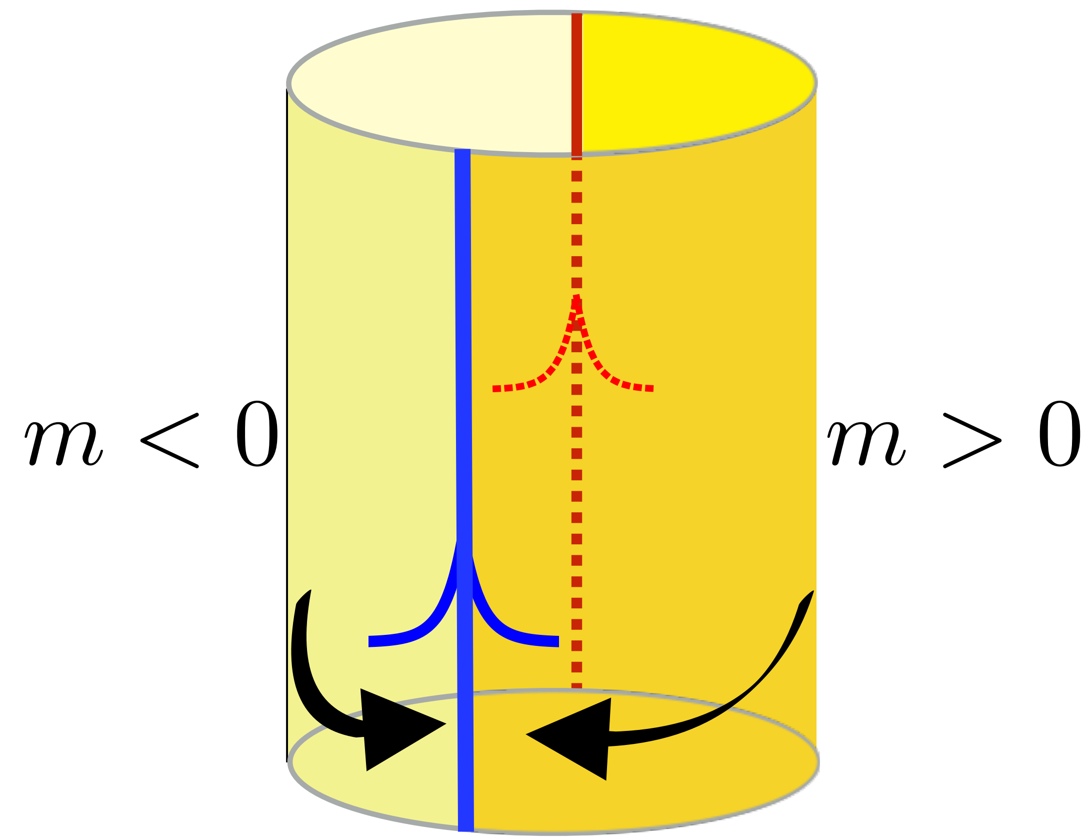
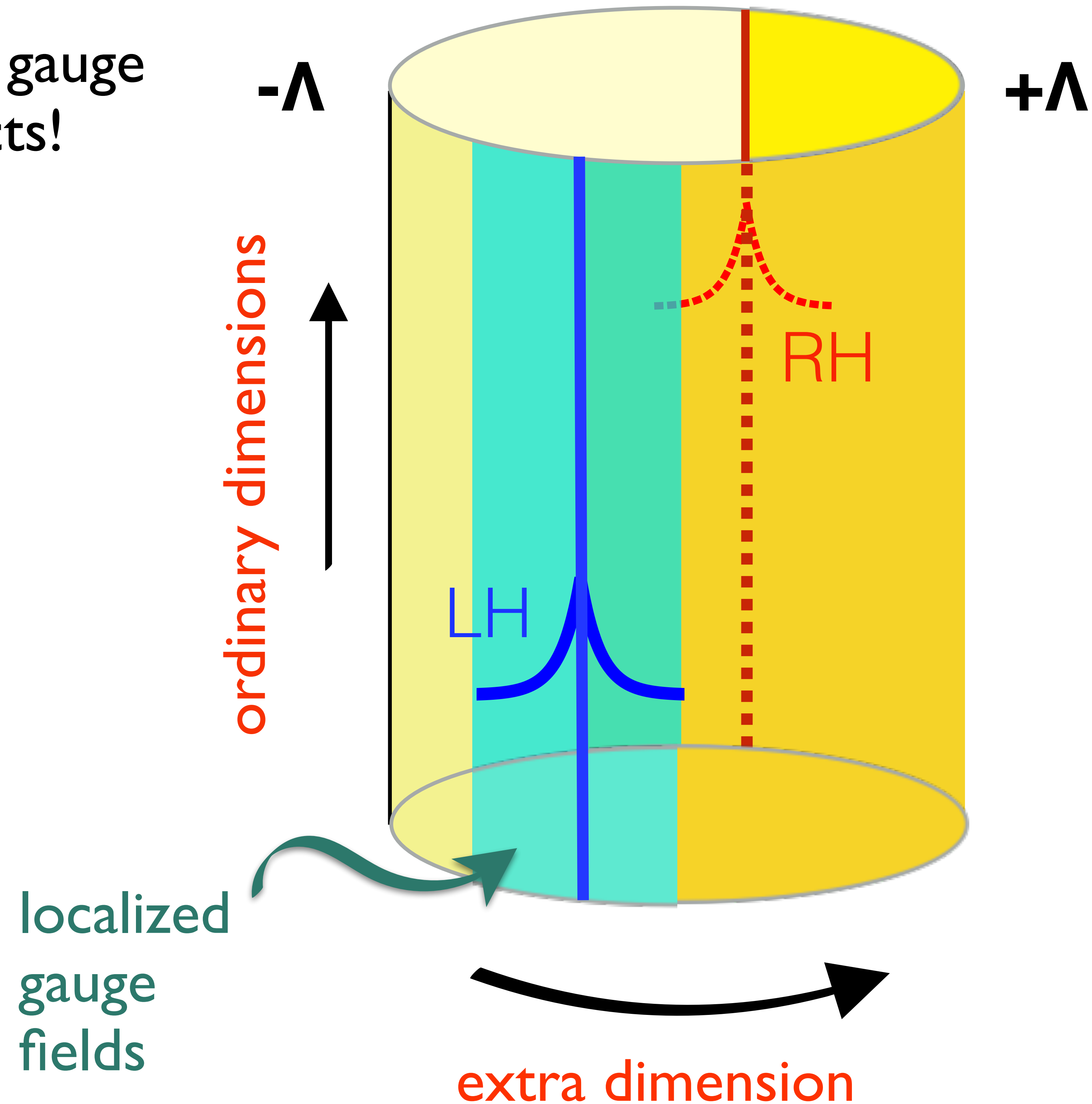
The simple model of 2 bulk fermions with opposite sign for the mass (so that the CS term cancels) is the Kane-Mele Quantum Spin Hall Effect (2004)



Old attempts to use domain wall fermions for chiral gauge theory

Obvious solution: localize the gauge fields around one of the defects!

- fermions = gauged
- mirrors = neutral



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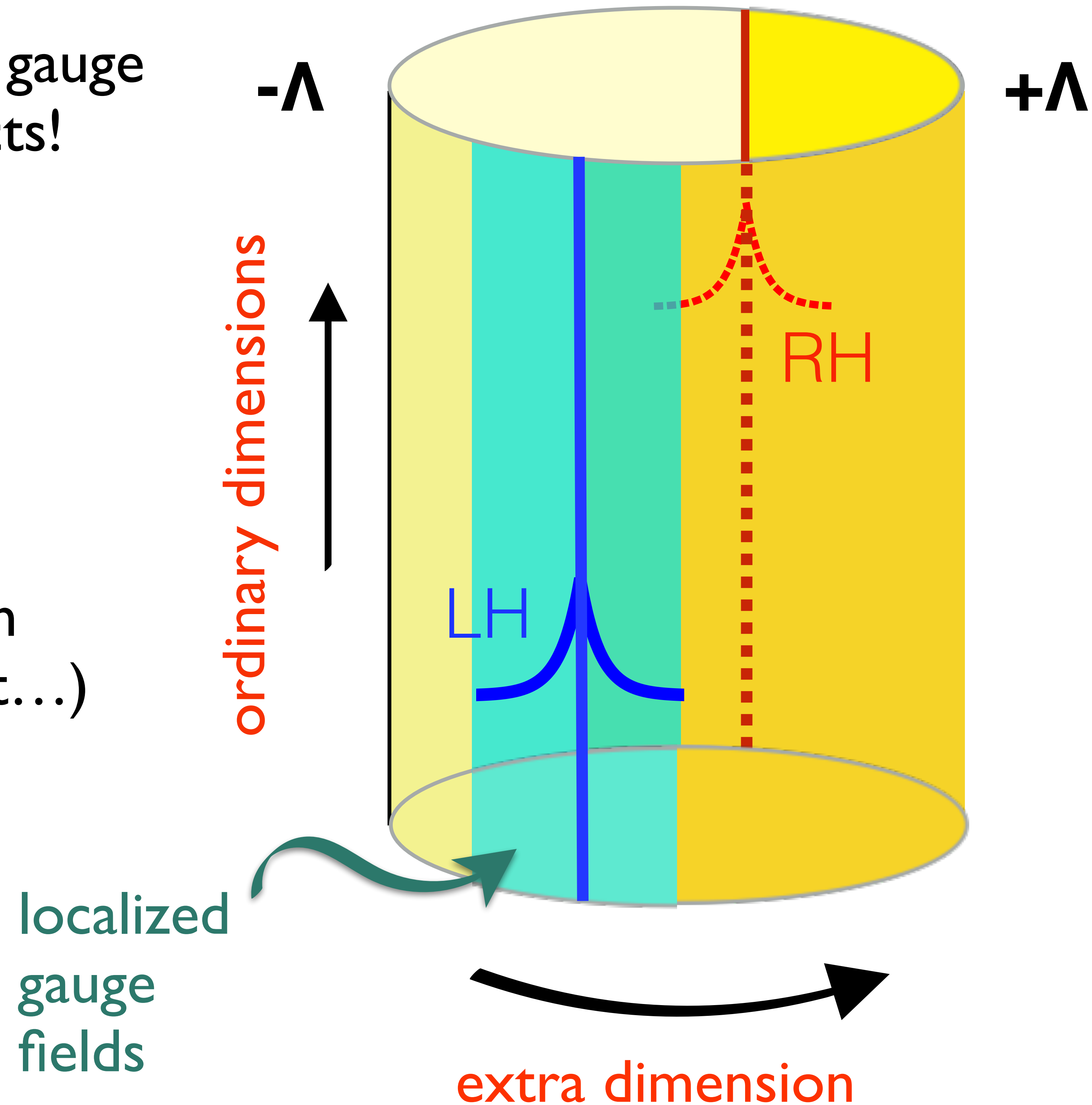
This requires:

- 5d gauge fields
- phase transition away from defect (Higgs, confinement…)



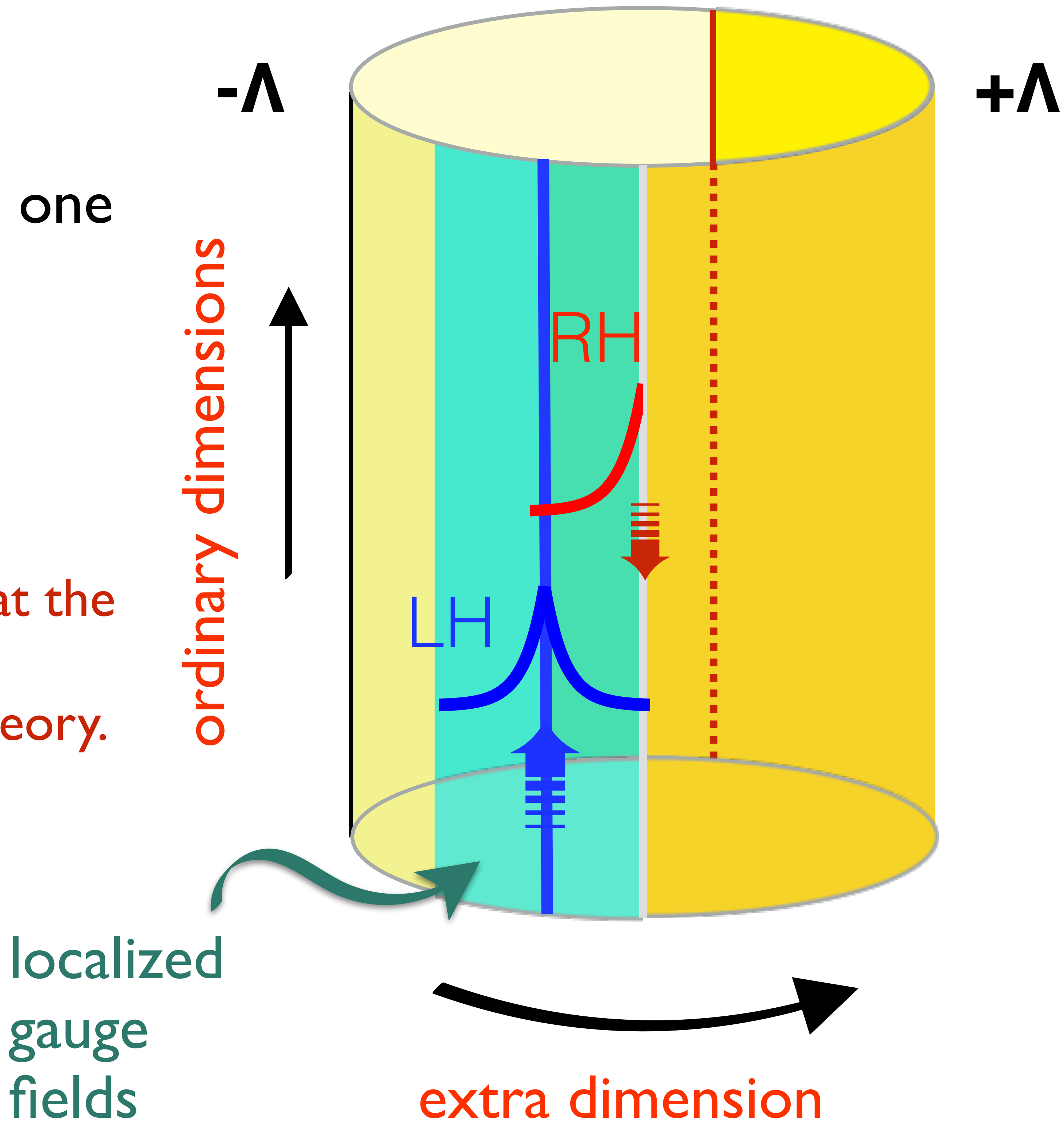
Old attempts to use domain wall fermions for chiral gauge theory

Localize the gauge fields around one of the defects?

Doesn't work.

Typically find new RH mode appears at the boundary of the SSB phase region
⇒ Dirac fermion, vector like gauge theory.

Golterman, Jansen, Vink 1993



Proposal: "localize" gauge fields for domain wall fermions using *gradient flow*

Technique introduced by mathematicians for smoothing manifolds

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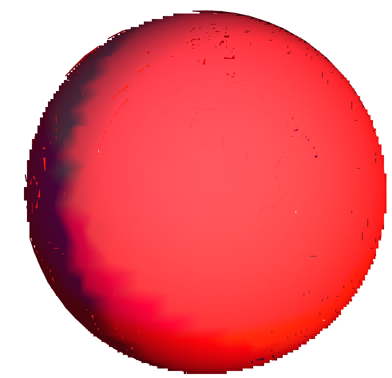

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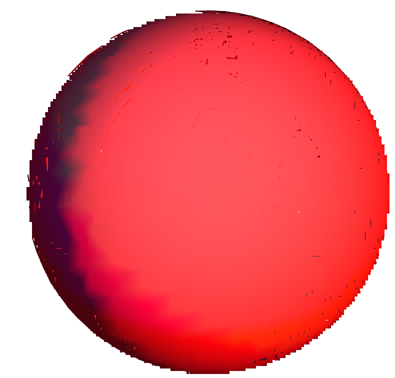

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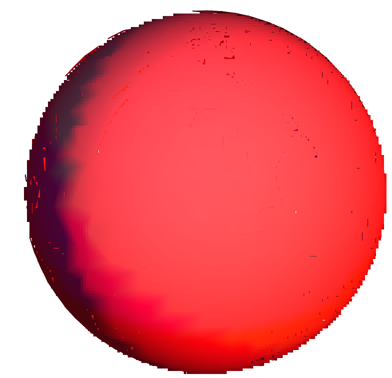

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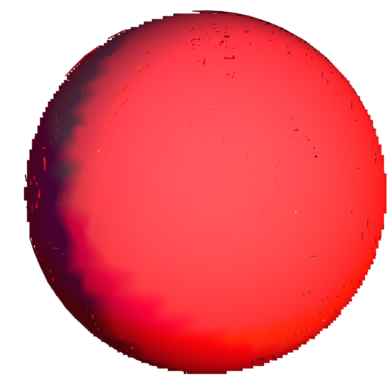

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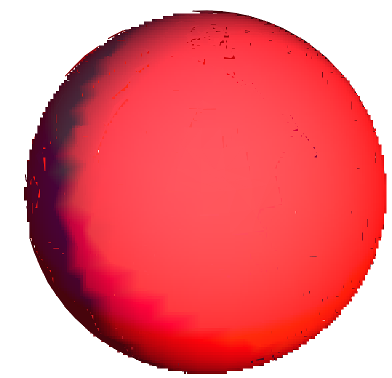
$\Rightarrow$ t



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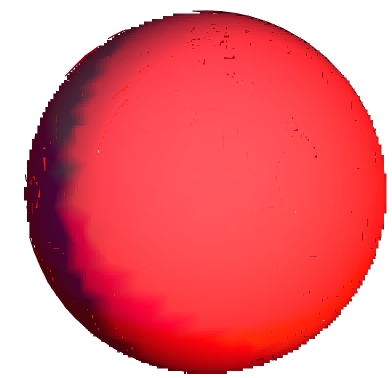

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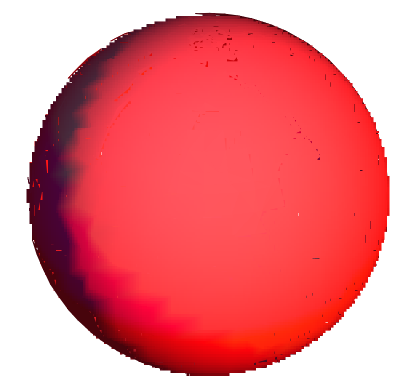

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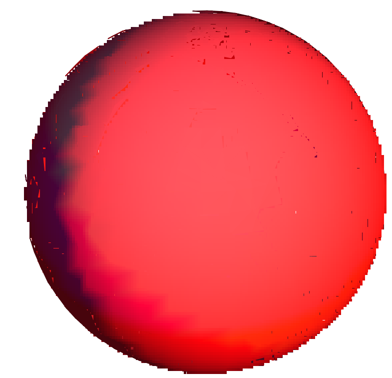

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- **diffeomorphism covariant**
- used by Perelman to prove Poincaré hypothesis

A scalar version of gradient flow

4d world

$\bar{\phi}(x,t)$ lives in 5d bulk

t

$$\frac{\partial \bar{\phi}}{\partial t} = \Box \bar{\phi}$$

flow equation
(= heat equation)

$$\bar{\phi}(x,0) = \phi(x)$$

boundary condition

$\phi(x)$ lives on 4d boundary of 5d world

Solution in momentum space: $\bar{\phi}(p,t) = e^{-p^2 t}\phi(p)$

Evolution in *t* damps out high momentum modes…looks like Gaussian form factor

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2d/3d U(1) example:

$$A_\mu \equiv \partial_\mu \omega + \epsilon_{\mu\nu}\partial_\nu \lambda \quad \Rightarrow \quad \partial_t \bar{\omega} = 0 \ , \qquad \partial_t \bar{\lambda} = \Box \bar{\lambda}$$

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This will allow λ(p) to be localized while maintaining gauge invariance

A **quantum** version of gradient flow for gauge fields (Lüscher, 2010)

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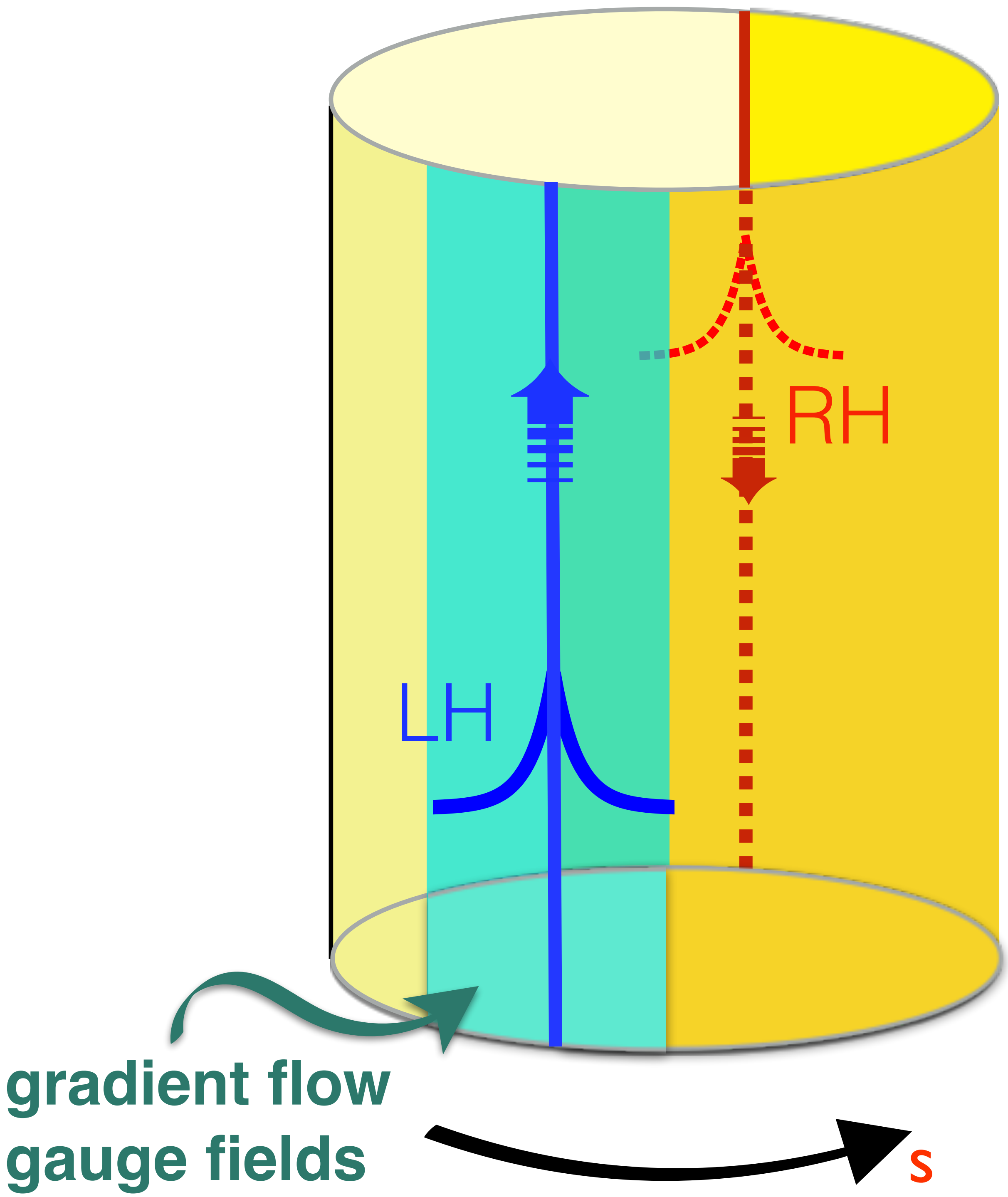
Integrate over surface field in path integral

Combining gradient flow gauge fields with domain wall fermions:

- quantum gauge field $A_\mu(x)$ lives at defect at s=0 where LH fermions live
- gauge field $\mathbf{A}_\mu(x,s)$ defined as solution to gradient flow equation with BC: $\mathbf{A}_\mu(x,0) = A_\mu(x)$
- flow equation is symmetric on both sides of defect
- RH mirror fermions behave as if with very soft form factor..."Fluff"...and decouple from gauge bosons*
- gauge invariance maintained



Concrete proposal for fermion "determinant" for chiral gauge theories:

$$\langle F(A) \rangle = \frac{\int [dA_\mu] e^{-S(A)} \Delta(A) F(A)}{\int [dA_\mu] e^{-S(A)} \Delta(A)} \ ,$$

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One factor for each 4d fermion

5d Dirac operator with flowed gauge field

Constant mass, cancels bulk fermion contributions

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Analytic, gauge invariant

What happens for anomalous theory?

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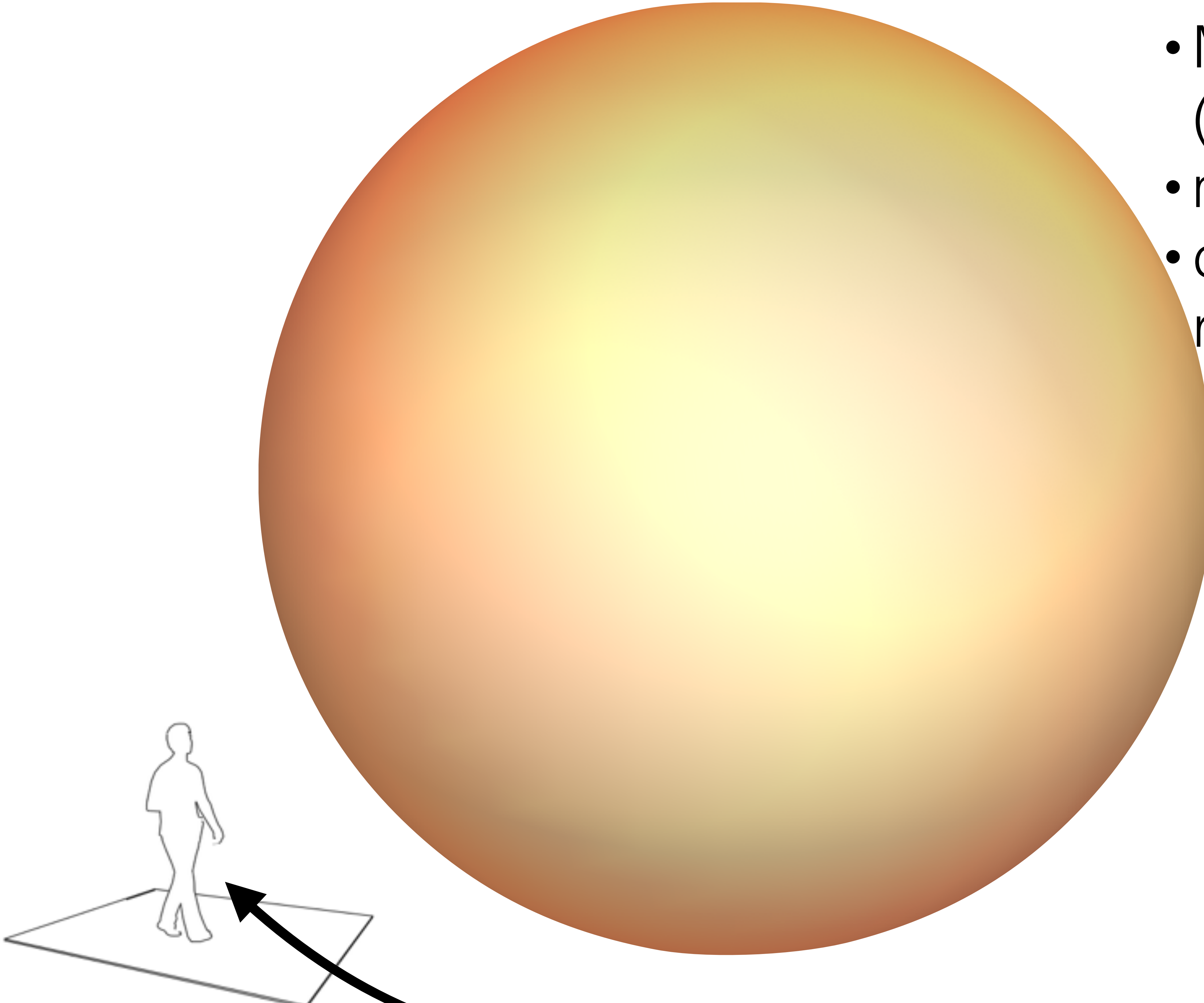
Anomalous representation of LH chiral modes:

- CS operator has nonzero coefficient
- With gradient flowed gauge fields this is not a local operator
- So one gets a gauge invariant theory, <u>but it is not 4d</u>…lost charges are "banked" in the extra dimension

Summary to this point:

- Proposal for measure for chiral gauge theories
- Involves marriage of domain wall fermions and gradient flow
- Manifestly gauge invariant
- Theory only looks local when fermion representation is anomaly free
- Involves mirror fermions with soft form factors that decouple… “Fluff”
- If fluff exists in the real world, could coupled to Ricci-flowed gravitational field and have non-canonical gravitational interactions



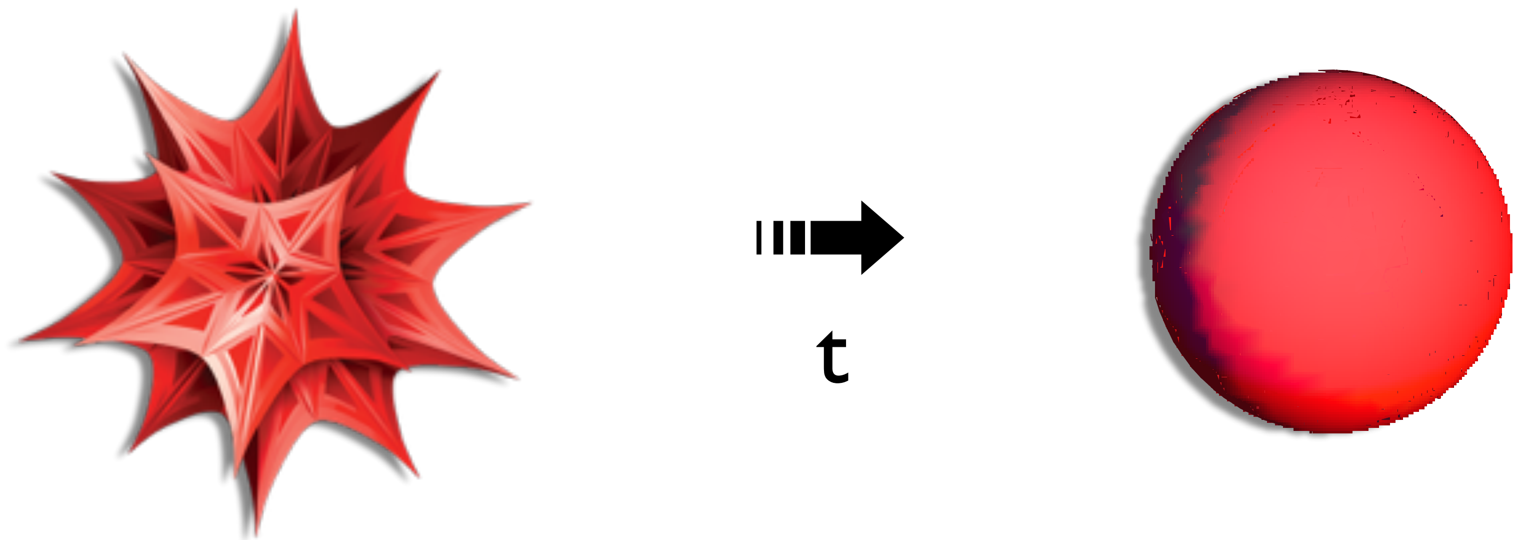
- Mirror top quark (fluff)
- mass = 170 GeV
- couples only to radio waves

- lattice gauge theorist

The whole story? No!

Flow equation: $$\frac{\partial \bar{A}_\mu(x,t)}{\partial t} = -D_\nu \bar{F}_{\mu\nu}$$

Rough configurations tend to flow to smooth ones



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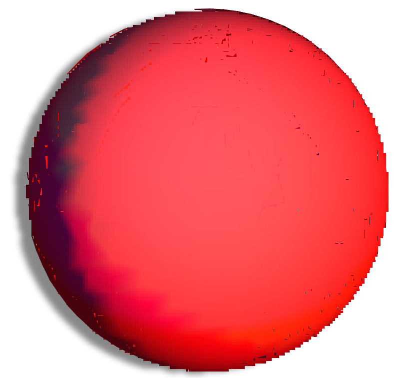

But solutions to the Euclidian equations of motion (in particular, instantons) do not flow at all

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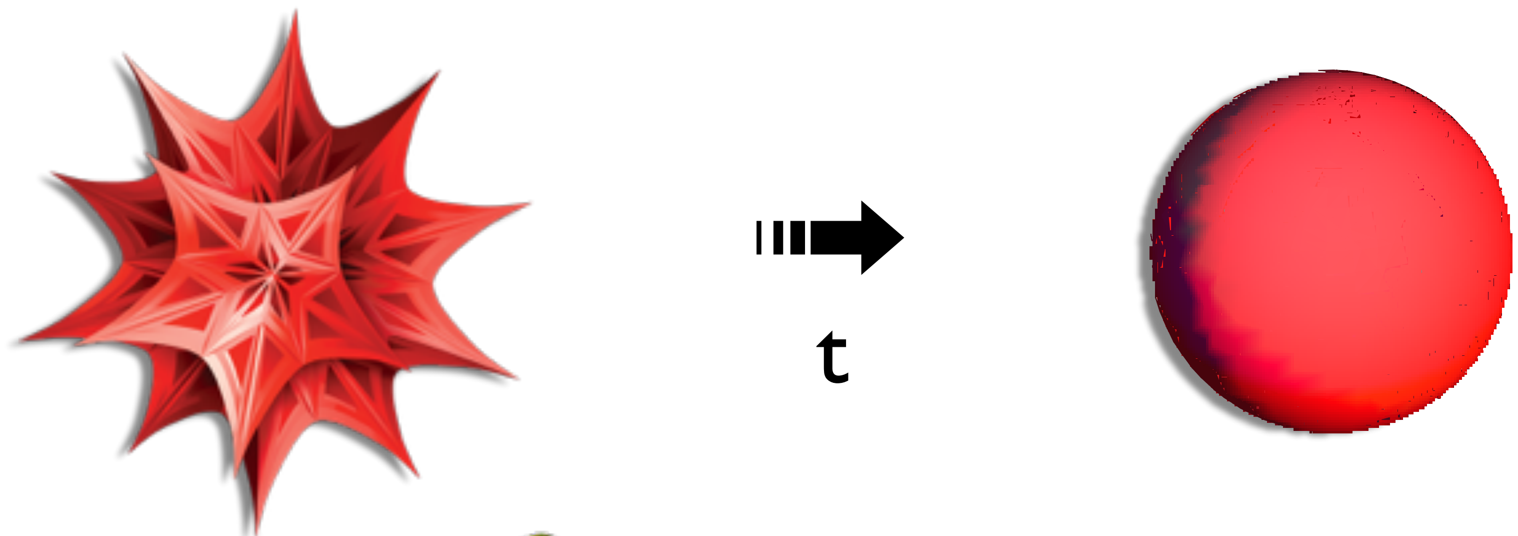

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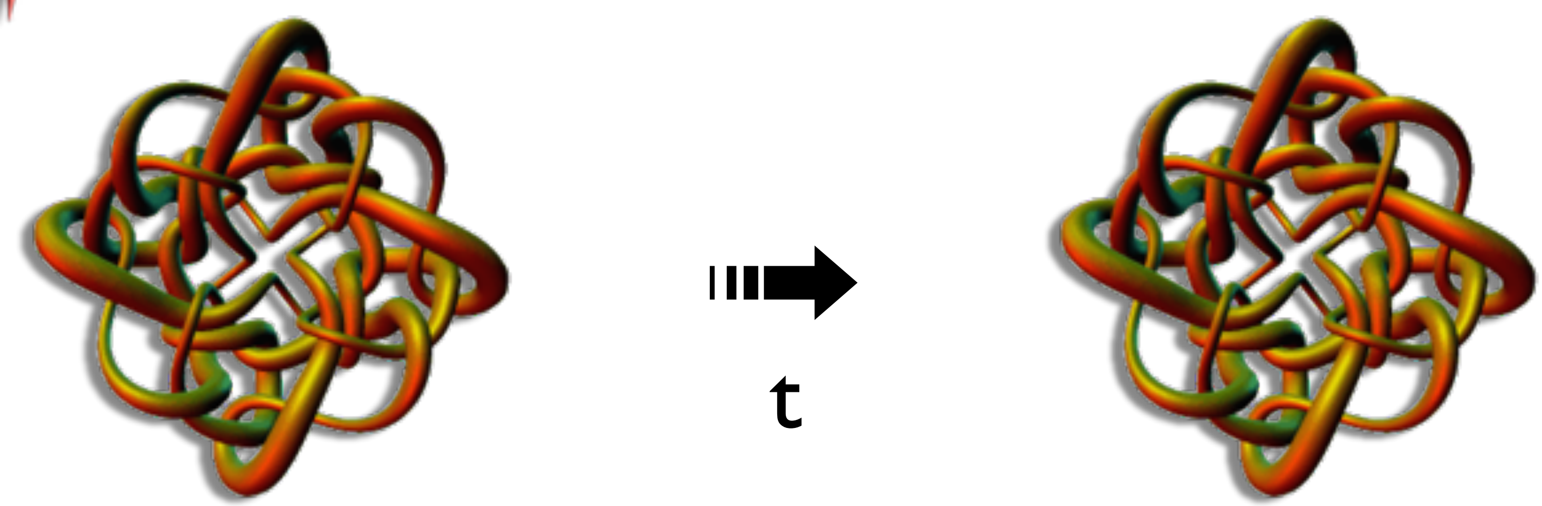
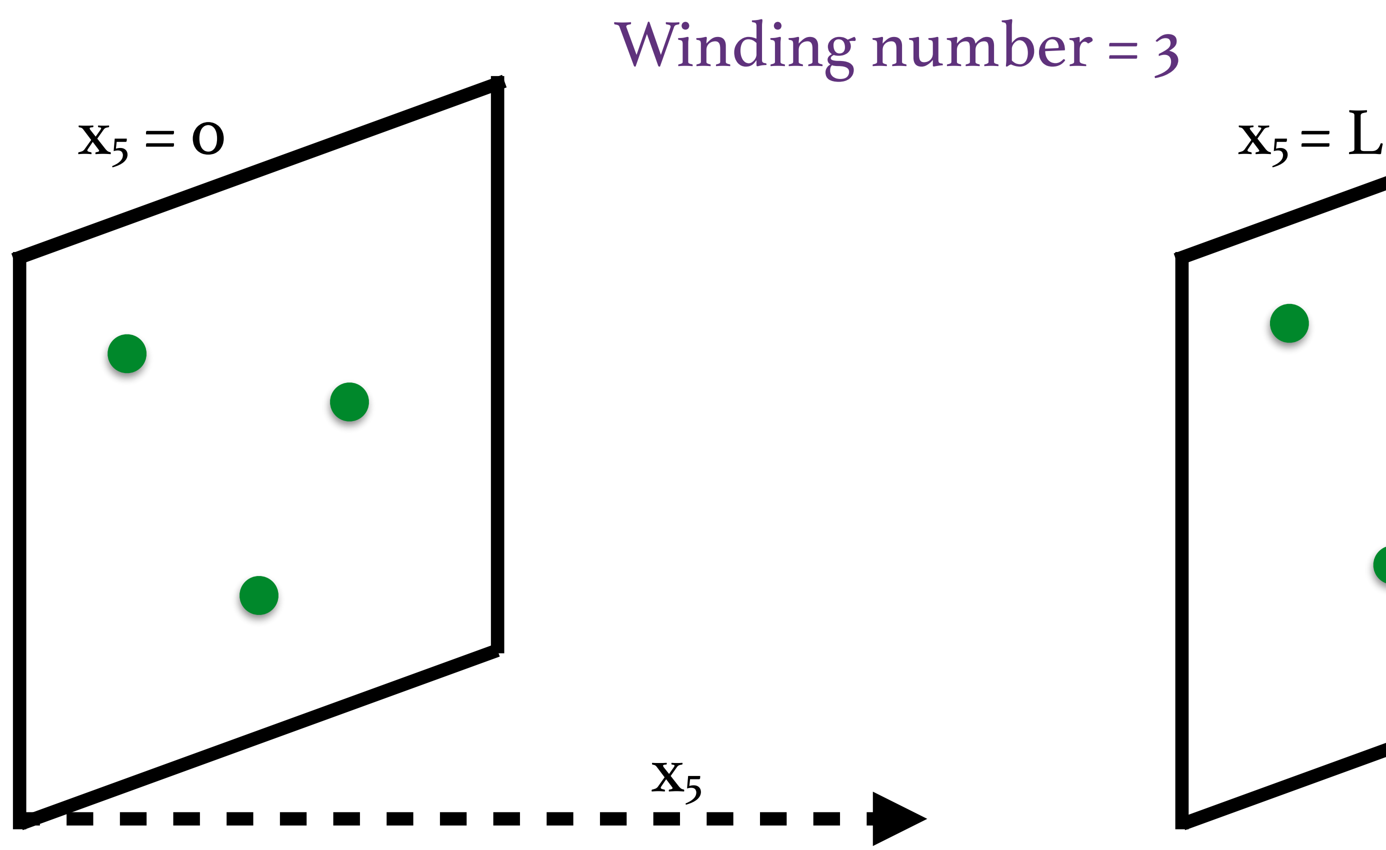


Fluff will not decouple from the topological features of the chiral gauge theory

Topological Gauge Configurations - Weak Coupling



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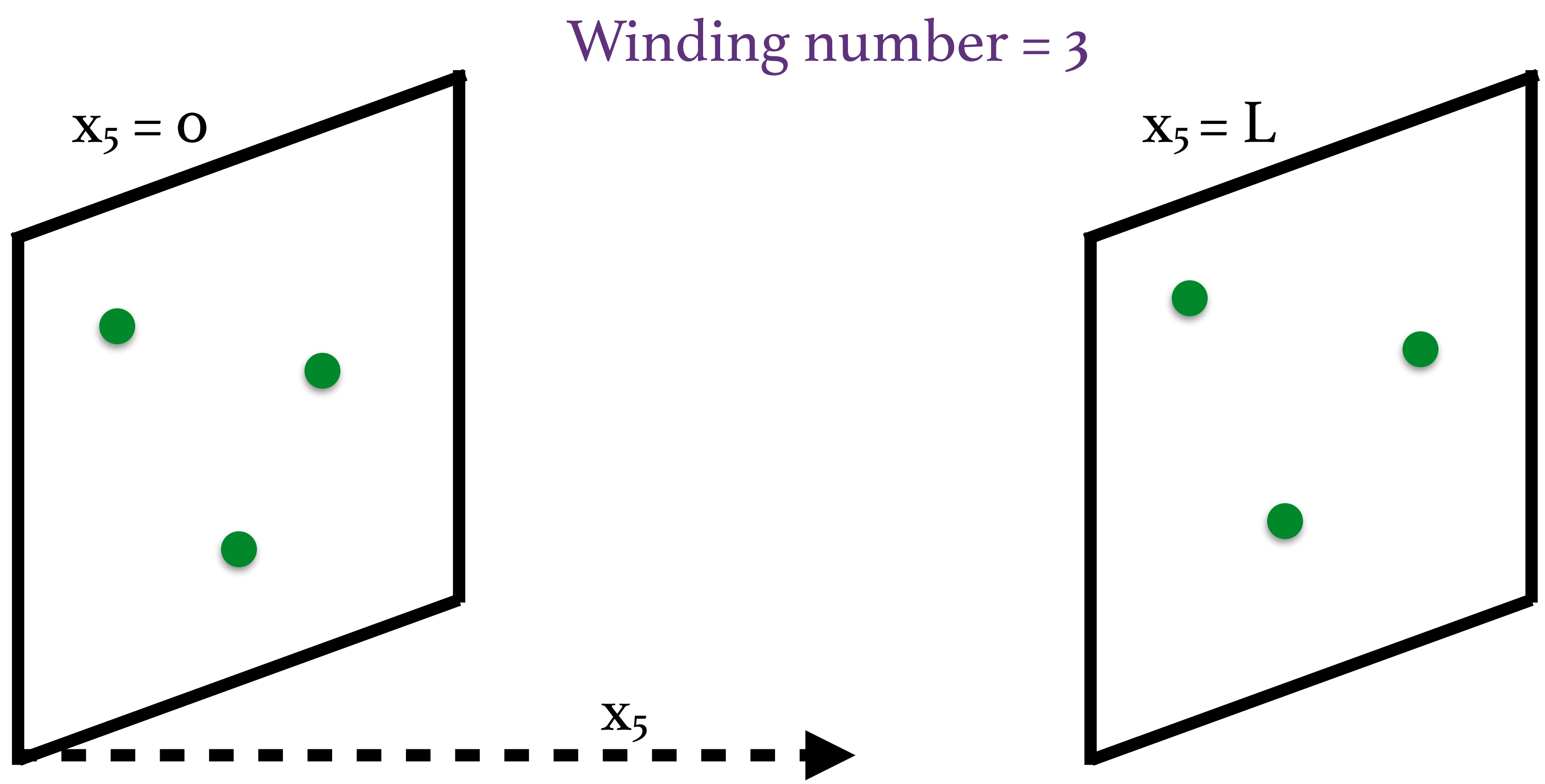
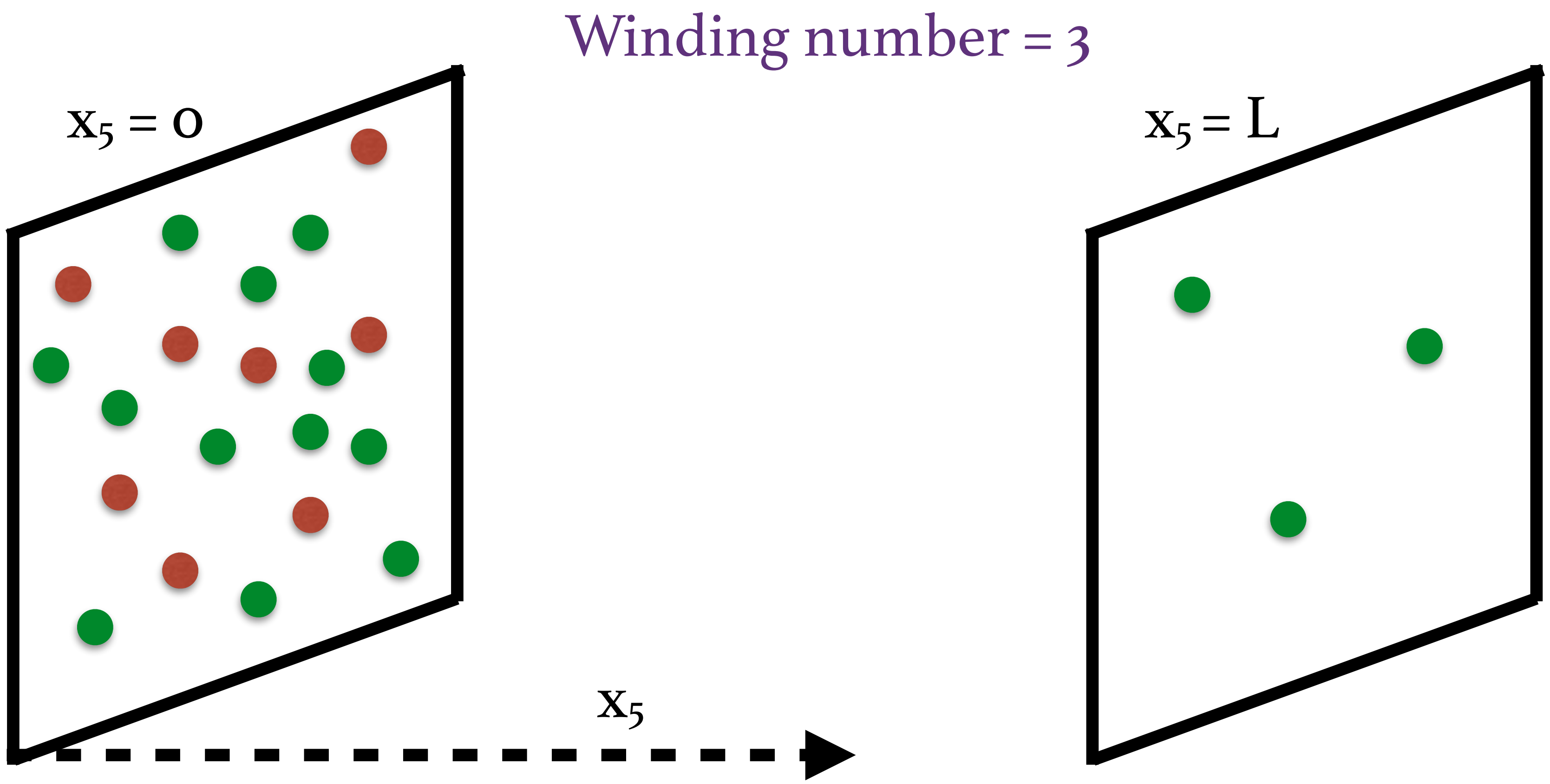


At weak coupling, minimal instanton contribution for given winding # is most important

- Flow does not affect location of instantons
- Correlation between location of instantons on the two boundaries allows for exchange of energy/momentum through 't Hooft vertices
- Weak coupling ⇒ exponentially suppressed process

Topological Gauge Configurations - Strong Coupling



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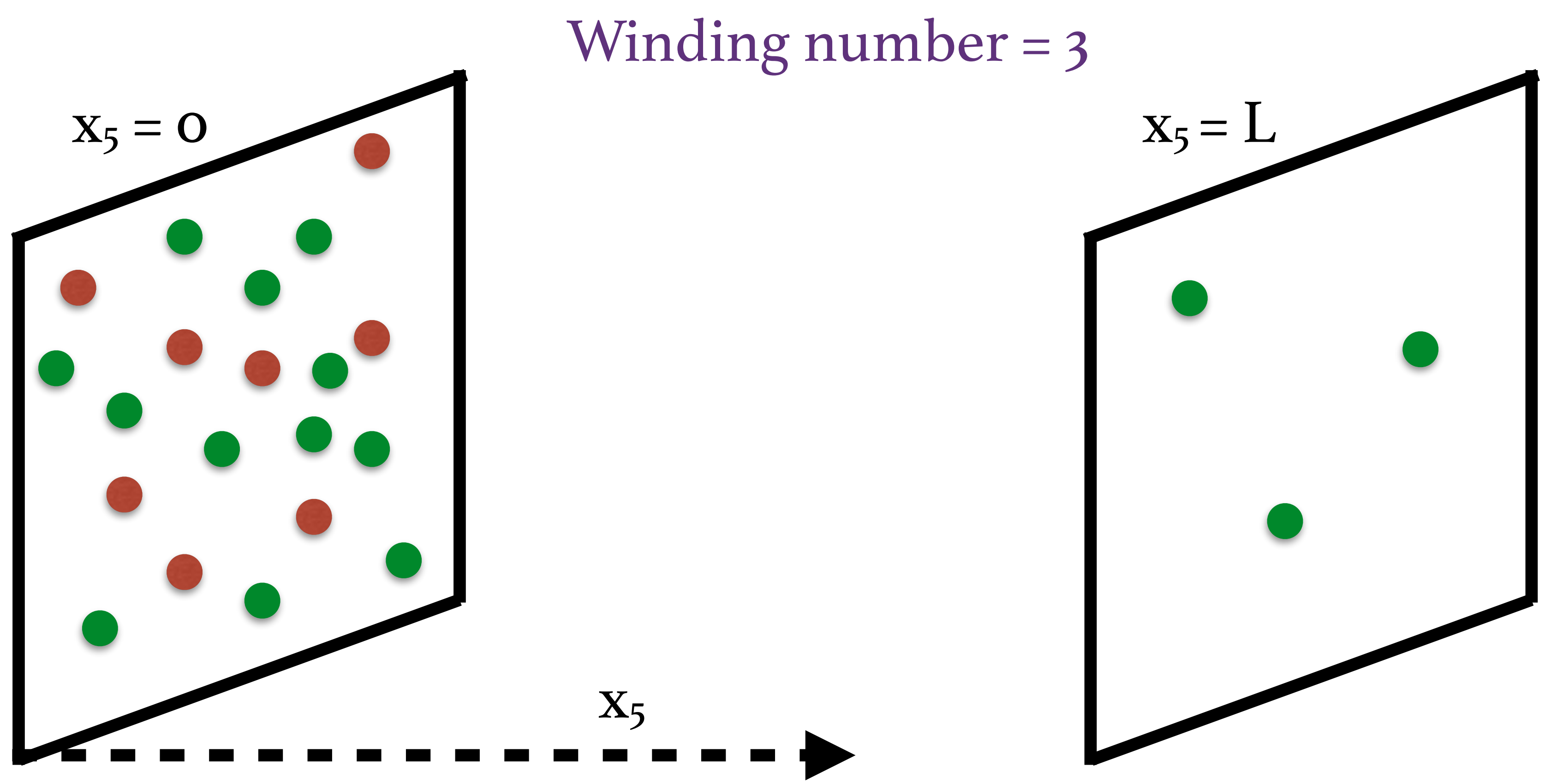

At strong coupling, need to include instanton-anti instanton pairs

- I-A pairs DO NOT satisfy equations of motion
- If flow for sufficiently large L, all pairs will annihilate
- Expect little correlation between location of fermion zero modes on the two boundaries
- Expect standard fermions and Fluff to interact via bi-local 't Hooft vertices but not exchange energy/momentum?

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- Motivated by a serious unsolved problem in QFT